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ORIGINAL ARTICLE

Problems of PGE metallogenesis related to mafic–ultramafic complexes in North Xinjiang, China

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Abstract Platinum group element (PGE) mineralization is mostly related to mafic–ultramafic complexes of the dominant magmatic deposit type. Mineralization of this type mainly relies on two conditions: the abundance of PGE in magma, and the presence of mechanisms favorable to PGE enrichment and separation from sulfur-saturated magma during magmatic evolution. Mafic–ultramafic complexes are widely developed in North Xinjiang, including (1) the large-scale copper-nickel deposits of Kelatongke, Huangshan, Huangshan East, and Tulargen, (2) numerous small to medium-sized copper-nickel deposits such as Xiangshan, Tudun, Hulu, Baishiquan, and (3) the Xiangshan West and Weiya medium-sized V–Ti magnetite deposits. However, mafic–ultramafic complexes in North Xinjiang rarely form PGE deposits. Therefore, questions about PGE metallogenesis in North Xinjiang are discussed in this paper from the standpoint of the ore-forming mechanism of PGE deposits and the characteristics of the North Xinjiang magma sources. The rock types of the post-collisional mafic–ultramafic complexes in North Xinjiang are of a ferrous rock series formed by fractional crystallization, a rock type generally favorable for hosting PGE. For the Cu-Ni sulfide deposits of North Xingjiang, the assimilation of crustal material causes sulfide liquation during processes of magmatic evolution and mineralization. This can be

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shown petrogeochemically, including the characteristics of Sr, Nd, Pb, O, Os, and S isotopes, which indicate a magmatic ore-forming mechanism for the Xingjiang PGE deposits. The principal reason for weak PGE mineralization in North Xinjiang may be ascribed to a widely-developed depleted mantle source (with positive ε_{Nd} values) that underlies it. The North Xinjiang lithosphere is not of typical Precambrian cratonal type, but has more affinities with modified oceanic lithosphere or immature continental lithosphere that would constitute PGE-poor original magma sources unfavorable to PGE mineralization.

1. Introduction

Platinum group element (PGE) resources in the world are mainly derived from mafic–ultramafic complexes that are closely related to magmatic Cu-Ni sulfide mineralization, layered intrusions with vanadium-titanomagnetite, and chromite mineralization; a few PGE-bearing black shale deposits are interesting exceptions not treated here. The Bushveld layered igneous intrusion in South Africa holds 75% Pt, 54% Pd, and 82% Rh of the world's PGE resources (Naldrett et al., 2008). PGE resources in China are relatively poor, and are mainly concentrated in the Jinchuan Cu-Ni deposit and the "Emeishan Large Igneous Province" of southwest China. They usually occur in mafic–ultramafic complexes with copper-nickel mineralization and vanadium-titanomagnetite mineralization (Tang and Li, 1996; Liu, 2002; Tang, 2004; Lai, 2006; Tang et al., 2006; Lv et al., 2007).

Mafic–ultramafic complexes are well developed in North Xinjiang, which hosts four large-scale copper-nickel sulfide deposits, namely Kelatongke, Huangshan, Huangshandong, and Tulergen, several medium-small sized Cu-Ni deposits like Xiangshan, Tudun, Hulu, and Baishiquan, and vanadium-titanomagnetite deposits such as Xiangshanxi and Weiya. However, no commercial PGE deposits have been found so far, and there is little PGE-accompanying mineralization in these Cu-Ni and vanadium-titanomagnetite deposits, except for in the Kelatongke Cu-Ni deposit. The prospecting potential for PGE deposits in this area has been explored by economic geologists and the Xinjiang Geology and Exploration Department with a view toward long-term development possibilities. Any discussion of this potential metallogenesis necessitates a thorough look at the relationship between PGE mineralization and host rocks.

2. PGE deposit review

2.1. Geochemical behavior of PGE

Magmatic PGE metallogeny is mainly associated with the nature of mantle-derived magma and processes of magma evolution. The mineralization process can be separated into four stages (Liu et al., 1984): (i) pyrolite melting and silicate, oxide, sulfide-entering melt phases, (ii) crystallization and differentiation of silicate melts, (iii) segregation of sulfide and other minerals with the capability of "collecting" PGE, and (iv) redistribution of PGE involving hydrothermal process.

In the partial melting process, PGE is intensively enriched in sulfide melts. Thus, only a small amount of PGE enters rock-forming minerals in the early stage of magmatism, but plentiful PGE can precipitate to form orebodies in the later evolution stage that accompanies chromite mineralization or is overprinted by Cu-Ni sulphide mineralization (Liu et al., 1984). Experimental results (Barnes and Picard, 1993) have shown that the distribution coefficients of platinum group elements in the process of partial melting are Pd (0.21) < Pt (0.68) < Rh (2.1) < Ru–Os–Ir (6.3), and decrease with an increase of oxygen fugacity (Bezmen et al., 1994; Fleet et al., 1999; Borisov and Palme, 2000). In other words, in the process of partial melting, Ir group PGE (Ir, Os, Ru) usually remain in the refractory phase (such as olivine, chromite, spinel, etc.) due to more difficult melting, whereas conversely, Pt group elements (Pt, Pd, Rh) are mainly retained in the early-forming melt phase (such as sulfides) because of their incompatible nature.

In crystallization differentiation, the distribution coefficients of PGE between the single-sulfide solid solution (solid phase) and residual sulfide melt (liquid) are Ir (3.4–11) > Os (4.3) > Ru (4.2) > Rh (1.17–3.03) > Pt (0.05–0.2) > Pd (0.09–0.2) (Fleet et al., 1999; Barnes et al., 2001). Therefore, Os, Ir, Ru, and Rh preferentially enter single-sulfide solid solutions, but Pt and Pd have priority to remain in the residual sulfide melt under sulfur-saturated conditions (as a segregation process). Experimental results (Brugmann et al., 1987; Capobianco and Braka, 1990) have also shown that Ir was not only controlled by the differentiation of sulfide, but also by the differentiation of olivine and chromite in crystallization. However, Pt group PGE are mainly controlled by the differentiation of sulfide and have less of a relationship with the crystallization of olivine and chromite. In other words, Ir group PGE can be concentrated in sulfides as well as in olivine and chromite, but Pt group PGE can only be included in sulfide phases.

During alteration and metamorphic processes, the geochemical behavior of PGE is mainly controlled by its solubility. The autometamorphism (serpentinization and uralitization) of mafic–ultramafic rocks can generate new minerals and lead to PGE redistribution. In the residual fluid of late magmatism, Pt and Pd can be transported as a fusible complex of $[HCO_3]^-$, S, and As. Experimental results have shown that the geochemical behavior of PGE is quite similar to Au. Whether in an oxidative hot brine or a reductive sulfur-rich and organic hydrothermal fluid flow through the source rock of precious metals, both PGE and Au can be dissolved into the solution and migrate as complexes (Molnar et al., 2001).

The formation of magmatic PGE deposits depends on two basic conditions. The first is that the magma contains abundant PGE, and the second is the existence of separating and enrichment mechanisms for PGE coming from the magma. On the basis of PGE geochemical behavior, the sulfur supersaturation from the mantle-derived magma during magmatic evolution and the subsequent separation of the sulfide and melt are favorable condition for the separation and enrichment of PGE. The condition leading to sulfur supersaturation is different in each type of magmatic PGE deposit (Su et al., 2007). For example, intensive magma differentiation accompanies large layered intrusion and an environment able to produce high R factor (the weight ratio of the original magma to sulfide melt) is required; crystallization differentiation and sulfide liquation are the favorable conditions for forming PGE deposits related to Cu-Ni sulfide mineralization.

2.2. The distribution and metallogenic types of PGE deposits

According to the U.S.G.S (2005), the world's PGE reserve is approximately 71 thousand tons, of which South Africa possess 63,000 tons, or ca. 88.7% of global reserves. South African PGE are concentrated in the Bushveld Igneous Complex, which has produced the famous Merensky, UG-2, and Platreef, among other major deposits. Other important PGE-producing countries are Russia (the Noril'sk-Talnakh area, Pechengga), the United States (Duluth, Stillwater), Canada (Sudbury, Voisey's Bay, Muskox), Zimbabwe (Great Dyke), and Australia (the Kambalda ore field). China's proven PGE reserves are approximately 350 tons (Lai, 2006), or 0.4% of worldwide reserves; its Jinchuan deposit holds 200 tons, or ca. 65% of Chinese reserves. China's second PGE-producing area is its southwest, which hosts the large-scale deposits of Jinbaoshan (ca. 45 tons) and Yangliuping (ca. 28 tons), and a number of medium- and small-sized deposits like Anyi, Zhubu, Xinjie, Huangcaoba, Qingshuihe, Reshuitang, and others. Other scattered PGE reserves are distributed in Henan (Zhouan), Heilongjiang (Wuxing), Hebei (Hongshila), Xinjiang (Kelatongke), and Inner Mongolia (Xiaonanshan).

Table 1 Rock assemblage of host mafic–ultramafic complex in North Xinjiang.

Rockbody type	Name of rockbody	Deposit scale	Outcrop area (km^2)	Rockbody shape	Lithofacies associations
Cu-Ni mineralization, post-collision	Kelatongke 1#	Large-scale	0.1	Spindle	biotite hornblende olivine norite, hornblende gabbro, biotite diorite, biotite hornblende norite
	Kelatongke 2#	Medium-size	Buried	Lenticular	biotite hornblende norite, biotite hornblende gabbro
	Kelatongke 3#	Medium-size	Buried	Lenticular	hornblende gabbro, hornblende norite
	Huangshan	Large-scale	1.71	Comet-like	gabbro-diorite, hornblende gabbro-norite, hornblende lherzolite, lherzolite, hornblende pyroxenite
	Huangshan East	Large-scale	2.8	Diamond lens	hornblende olivine-gabbro, hornblende gabbro, gabbro-diorite, hyperite, olivine hyperite, hornblende lherzolite
	Huangshan South	Medium-sized	4.22	Lenticular	hornblende lherzolite, peridotite, hornblende pyroxenite, lherzolite, hornblende gabbro, norite
	Huangshan North	Mineralization	9	Annular lens	pyroxenite, peridotite, gabbro, diorite
	Xiangshan (Middle)	Medium-sized	0.55	Lenticular	hornblende peridotite, peridotite, norite, pyroxenite, hornblende gabbro
	Tudun	Medium-sized	0.9	Irregular oval	gabbro, hornblende lherzolite, hornblende pyroxenite
	Hulu	Medium-sized	0.75	Lenticular	peridotite, pyroxenite, lherzolite
	Mati	Small-sized	0.15	Clevis	hornblende peridotite, hornblende lherzolite, peridotite,
	Tulaergen	Large-scale	<0.005	Lenticular	lherzolite, hornblende peridotite, hornblende pyroxenite, gabbro
	Baishiquan	Small-sized	3.2	Irregular oval	diorite, gabbro, norite, pyroxenite, peridotite
	Poshi	Small-sized	3.2	Oval	peridotite, pyroxenite, lherzolite, olivine-gabbro, hyperite
V-Ti-Fe mineralization, post-collision	Weiya	Medium-sized	1.4	Irregular	alkaline olivine-gabbro, hornblende lherzolite, hornblende gabbro, hornblende anorthosite
	Southwest of 1073 High Point	Small-sized	2.2	Tadpole like	hornblende gabbro, gabbro-diorite
CuNi-VTiFe mineralization, post-collision	Xiangshanxi	Medium-sized	1.6	Spindle	pyroxenite, lherzolite, olivine-gabbro, hornblende gabbro, ferrogabbro,Ti-bearing hornblende gabbro, leucogabbro
	Niumaoquan	Small-sized	4.5	Irregular cycle	olivine norite, Ti-bearing olivine-gabbro, Ti-bearing hornblende gabbro, hornblende anorthosite
	Erhongwa	Small-sized	7.67	Irregular cycle	lherzolite, hyperite, olivine-gabbro, pyroxene diorite, quartz diorite
	Haladala	Mineralization	22	Beanpod lenticular	gabbro, diabase, diabase-gabbro, olivine-gabbro, troctolite, pyroxene anorthosite
Cu-Ni mineralization, Hercynian	Jingbulake	Medium-size	2.4	Eyeball shape	peridotite, olivine-gabbro, gabbro, diorite
Cu-Ni mineralization, Middle Proterozoic	Xingditage 2#	Small-sized	10	Asymmetric wedge	peridotite, pyroxenite, lherzolite, gabbro

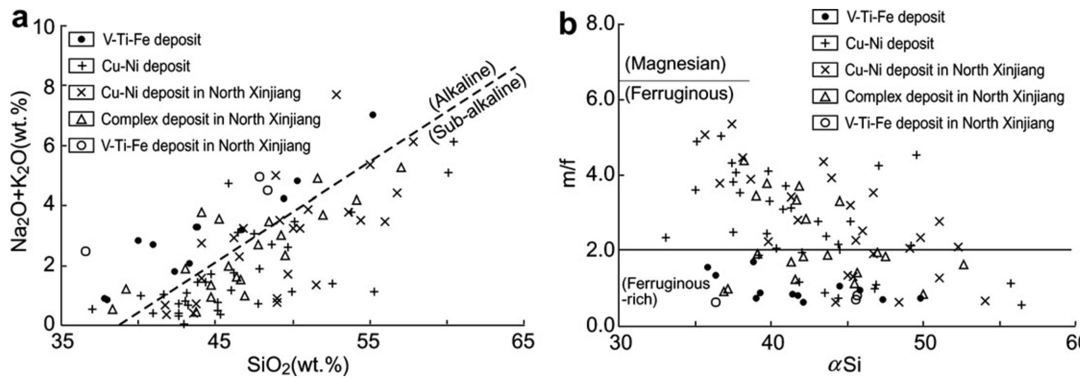

Figure 1 Alkaline vs. SiO_2 diagram (a) and m/f (mafic ratio) vs. αSi (acidity index) diagram (b) of ore-bearing mafic–ultramafic rocks from North Xinjiang and other areas. a – from Irvine and Baragar (1971), b – from Qiu and Lin (1991).

The present classification of PGE deposits is made according to various criteria established by different authors. Hulbert et al. (1988) divided PGE into the three types of magmatic, hydrothermal, and supergene by metallogeny; Liu (2002) divided PGE into the seven sequences of CuNiS-PtPd, FeCr-OsRuPtIr, FeTiV-PtPd, CuNiAu-PtPd, CuMoFe-OsPtPd, TeAsSbBi-PtPd and NiMoVUAu-PtPd by element assemblages; Naldrett (2004) divided magmatic sulfide PGE deposits into stratabound (including the two sub-types of stratiform and non-stratiform, and the three associations of sulfide, chromite, and magnetite-apatite) and discordant-to-strata types on the basis of morphology and mineral association; Su et al. (2007) divided PGE into six categories according to host rocks, namely the layered mafic–ultramafic complex type which is associated with the mafic–ultramafic Cu-Ni sulfide type, the Urals complex type, the ophiolite-connected type, the hydrothermal-associated type, and the exogenous type.

Metallogenic types of PGE are varied, especially because the recent discovery of the Russian Suhoyipot Au–Pt deposit has highlighted the importance of black shale-type PGE deposits (Liu et al., 2004). However, mafic–ultramafic complexes are still the dominant source rocks for PGE deposits, and magmatic type deposits are the dominant PGE metallogenic type. The important ore-bearing complexes of magmatic PGE deposit are layered intrusions, small differentiated mafic–ultramafic rock bodies (generally smaller than 10 km^2 in surface area), and komatiites. The first two are the main PGE-producing rock body types both worldwide and in China.

3. Geochemical characteristics and metallogenic mechanisms of magmatic ore deposits in North Xinjiang

3.1. Ore-bearing mafic–ultramafic rocks and their PGE-bearing characteristics

Mafic–ultramafic rocks are widely exposed in North Xinjiang (north of approximately latitude 40°), and mainly belong to small differentiated rock bodies (generally less than 10 km^2 in surface area; Table 1). On the basis of mineralization characteristics, these deposits can be divided into three types. The first is connected with Cu-Ni sulfide mineralization in a mainly tholeiitic igneous rock association including hornblende peridotite, hornblende pyroxenite, hornblende lherzolite, olivine-gabbro, hyperite, and hornblende gabbro, with a minor calc-alkaline rock series

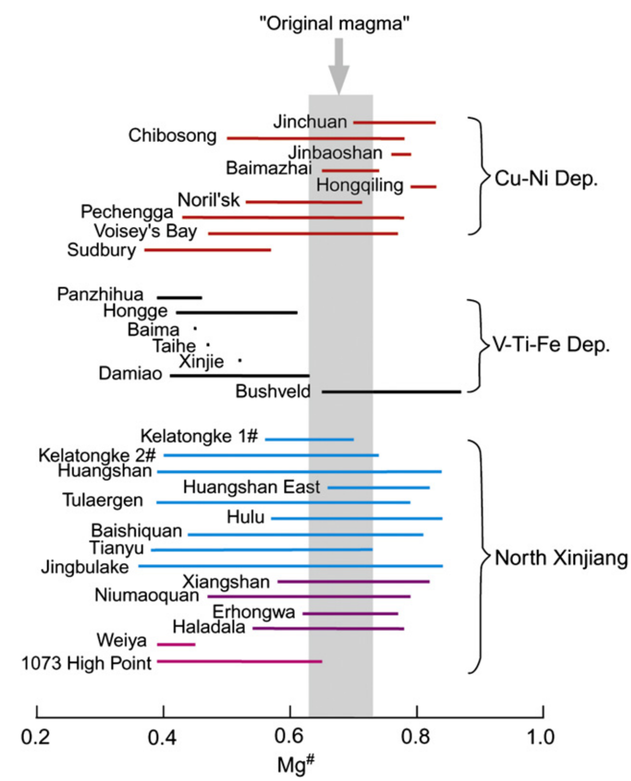

Figure 2 Range of $Mg^{\#}$ value of host mafic–ultramafic rocks from North Xinjiang and other areas. Annotation: the $Mg^{\#}$ value is the range of the average value of different rock types; The original data sources from: Jinchuan, Hongqiling, Noril'sk - No. 6 Geological Party of Gansu Bureau of Geology and Mineral Resources (6GPGB) (1984); Chibosong, Jinbaoshan, Baimazhai -Tang et al. (2006); Pechengga, Voisey's Bay, Sudbury -Naldrett (2004); Panzhihua, Hongge, Baima, Taihe, Xinjie -Zhang et al. (1988); Damiao -Xie (1980); Bushveld -Harmer and Sharpe (1985); Kelatongke 1# -Wang and Zhao (1991); Kelatongke 2# -Ran and Xiao (1994); Huangshan -Mu (1996); Huangshan East -Zhang (1987); Tulaergen, Hulu -Sun et al. (2007); Baishiquan -Chai et al. (2006); Jingbulake -Sun and Ni (2008); Xiangshan West -Wang et al. (2009); Weiya -Wang et al. (2005); Tianyu, Niumaoquan, Erhongwa, Haladala, southwest of High Point 1073 -this paper.

(the Kelatongke). They mainly form in a Permian post-collisional stage (Mao et al., 2006; Wang and Xu, 2006), with the exception of the Middle Proterozoic Xingditage 2# Cu-Ni deposit (Li et al., 1991, 1998) and the Jingbulake Cu-Ni deposit of middle Devonian or early Carboniferous age (Zhang Z.H. et al., 2006b). The second type is small stratiform-like rock bodies, related to vanadium-titanomagnetite mineralization, and represented by the Weiya deposit. Its rock association is characterized by alkali-rich, high Ti content hornblende lherzolite, olivine-gabbro, hornblende gabbro, and hornblende anorthosite. The third type is related to Cu-Ni and V-Ti-Fe complex mineralization in mainly calc-alkaline layered or stratiform-like structures with dual characteristics of the first and second types (Fig. 1a).

Fig. 1b illustrates that the m/f (mafic ratio) value of ore-bearing mafic−ultramafic rocks in North Xinjiang is basically in accord with that of worldwide PGE-bearing Cu-Ni sulfide deposits and vanadium-titanomagnetite, and that they belong to ferruginous or ferruginous-rich mafic−ultramafic rocks, that are advantageous for PGE mineralization. The mafic−ultramafic rocks of vanadium-titanomagnetite deposits in North Xinjiang are ferruginous-rich with m/f values lower than 2.0; and the copper-nickel sulfide deposits are ferruginous with higher m/f values of 2−6.5. The m/f values of complex deposits and Cu-Ni deposits in North Xinjiang can be more or less than 2.0, which indicate the dual character of ferruginous-rich and ferruginous rocks.

Usually, the $Mg^{\#}$ value of original magma ranges from 0.63 to 0.73 (Green, 1975). The mafic−ultramafic rocks of the North Xinjiang study area have $Mg^{\#}$ values that vary widely within a range of 0.36−0.84 (Fig. 2), a phenomenon which is possibly derived from the evolution of magma. Most values (<0.63) may indicate a fractional crystallization of olivine which occurs in accord with the lower Fo values (percentage of forsterite molecule in olivine) of olivine minerals in the area (Pan et al., 1994; Chai, 2006; Qin et al., 2007): Kelatongke (Fo = 74.9−81), Huangshan East (70−83), Tulaergen (82−84), Xiangshan (81.68−83.49), Huangshan South (83−86), and Baishiquan (78−85). High Fo values in olivine indicate the direct crystallization of original magma in the deep magma chamber, whereas low-Fo values may result from evolution of the original magma by way of differentiation and crystallization.

The previous mineralogical study shows that the Ni content of olivine in the copper-nickel deposits of North Xinjiang is quite low, which may indicate that the fractional crystallization of olivine is distinctly accompanied by the segregation of sulfide melts (Chai, 2006; Qin et al., 2007; Li, 2008). Because PGE tend to be enriched in sulphide melts, crystallization differentiation should be favorable to the enrichment of PGE. In other words, the Cu−Ni-bearing complexes in North Xinjiang are provided with one of the essential PGE-forming conditions: fractional crystallization.

3.2. Metallogenic mechanisms restricted by the geochemistry of ore deposits

The Platinum Group elements, in particular the Pt-group PGE (PPGE), are predominantly hosted in sulfide phase of magmas, and thus the liquation or immiscibility of sulfides plays a critical role in PGE mineralization. Study of most Cu-Ni sulfide deposits reveals that the liquation of sulfides is due to a sulfide-rich liquid phase losing balance with the magma phase, which induces liquid immiscibility because of the sulfur oversaturation in magma (Rad'ko, 1991; Brugmann et al., 1993; Naldrett et al., 1993). Examples such as the Noril'sk, Voisey's Bay, Sudbury, Duluth, and Jinchuan suggest that, in addition to fractional crystallization, factors such as magma mixing, the addition of allochthonous sulfur, and assimilation and contamination by silica-rich wall rocks are all important reasons for sulfideliquationfrom silicate melts (Ripley, 1981; Grinenko, 1985; Lesher and Campbell, 1993; Li and Naldrett, 1993; Liu, 1993; Naldrett et al., 1993; Lightfoot and Hawkesworth, 1997; Naldrett, 1999; Li et al., 2000; Su et al., 2004).

Although it has been confirmed that the liquation of the Noril'sk and Pechengga deposits is caused by allochthonous sulfur, this does not

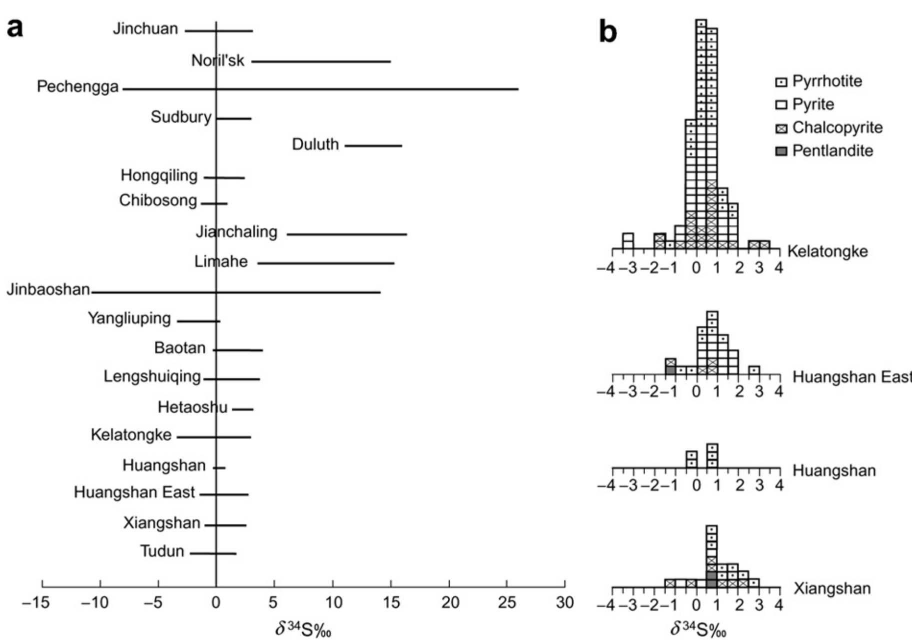

Figure 3 Sulfur isotope of Cu-Ni(-PGE) deposit from North Xinjiang and other areas. The original data of North Xinjiang sources from: Kelatongke -Pan et al. (1994), Wang and Zhao (1991); Huangshan East-Wang et al. (1987), and partly from this paper; Xiangshan -Li et al. (1996), and partly from this paper. Other deposits data source from Yao (1988), Luo (1992), Liu et al. (2004), and Tang et al. (2006).

necessarily lead to sulfide immiscibility for Cu-Ni sulfide deposits like Sudbury, and Jinchuan (Fig. 3a). The S isotope of the Cu-Ni sulfide deposits in North Xinjiang is characterized by a normal school modal with the peak value of near zero and a narrow $\delta^{34}S$ range of −3.49‰ to +3‰ (Fig. 3b). This indicates that the sulfur is basically sourced from the mantle without any obvious additions from wall strata.

However, the evidence from Sr, Nd, O, Pb, and Os isotopes and trace elements indicates that the magma of these Cu-Ni sulfide deposits in North Xinjiang is indeed contaminated by crustal materials to a certain degree. For example, the $^{87}Sr/^{86}Sr$ initial ratio of magmatic host rocks for these deposits varies within a range of 0.7016–0.7062 (Zhou et al., 2004; Chai, 2006), which is generally higher than the MORB value (0.70229–0.70316, from Saunders et al. (1988)) and implies that these deposits may be contaminated by earth crust. From the statistical results of oxygen isotopes, the $\delta^{18}O$ (‰) value of the host mafic–ultramafic rocks ranges from 5.4 to 11.21, with a value higher than 6.0 in most sample (87.5%; Chai, 2006; Zhang Z.C. et al., 2006a; Wang, 2009). This also indicates that the crustal material has contributed to the magma source (Kyser et al., 1986). The trace elements of mafic–ultramafic rocks are characterized by enrichment of large-ion lithophile elements (LILE) and light rare earth elements (LREE), and are relatively depleted in high field strength elements and high La/Sm and Th/Ta ratios (Wang Y.W. et al., 2004c,d; Sun et al., 2006; Zhang Z.C. et al., 2006a; Meng, 2008). These characteristics are all indicative of the hybridism of igneous melts by continental crust. In addition, Re–Os isotopic characteristics of sulfide indicate that some Os comes from the continental crust: the $^{187}Os/^{186}Os$ initial ratio of Kelatongke, Huangshan East, Xiangshan, and Baishiquan is from 0.25 to 0.68. The values of $\gamma_{Os}(t)$ in Cu-Ni sulfide deposits range from +99 to +482 (Mao et al., 2002; Zhang et al., 2005; Han et al., 2006; Li et al., 2006; Wang et al., 2007) — obviously lower than those of Sudbury (+430 to +814; Walker et al., 1991) and Voisey's Bay (+200 to +1100; Lambert et al., 1999), but higher than Jinchuan (+16.1 to +35.2; Zhang et al., 2004; Yang et al., 2007) and Noril'sk (+4.1 to +14.2; Walker et al., 1994).

Conditions favorable to magmatic sulfide deposits include the generation of sulfide-bearing melt by interfusion of continental crust, which either decreases the sulfur solubility in magma due to an increase of Si and Fe and decrease of Mg contents (Tang et al., 2006), or else increases sulfur activity due to an increase in magmatic alkalinity by K and Na joining (Luo et al., 2000). With no particular differences to be found when comparing the same deposit types found both in China and around the world, the addition of continental crust into the North Xinjiang copper-nickel sulfide deposits is the main factor which induces the immiscibility and liquation of sulfide. In other words, although conditions favorable to PGE mineralization appear to exist in North Xinjiang, why have they not yielded significant mineralization in this area? In addition to the addition of continental crust, what are the other unfavorable factors?

4. Characteristics of earth's crust in North Xinjiang

4.1. The PGE characteristics of mafic–ultramafic rocks in North Xinjiang

The PGE contents of sulfide ore from the copper-nickel deposits of North Xinjiang are mostly less than the cutoff grade of 0.3 g/t (Table 2), except for orebody #1 and #2 of Kelatongke and several samples from Tulaergen. Recalculation of PGE content in 100 percent sulfide ore from deposits at Kelatongke is in the range of 99–2645 ppb (average of 573 ppb), and at Tulaergen in the range of 407–1866 ppb; both are about two orders of magnitude lower than PGE in the Russian Noril'sk-Talnakh region (82,209 ppb average; Naldrett, 2004), and one order of magnitude lower than that of Jinchuan (3248 ppb average; Tang and Li, 1995) and Canada's Sudbury area (5964 ppb average; Naldrett, 2004).

Two possible factors may lead to the low degree of PGE mineralization in the Cu-Ni deposits of North Xinjiang. One is the low PGE concentration in original melts, and the other is prior liquation and/or the escape of PGE-carrier sulfide before parental magma generation. Based on simulation, calculation of the R-factor, and PGE contents in parental magma at the Kelatongke deposit, Qian et al. (2009) posited that PGE was not deficient in original magma, but that fractional crystallization of olivine and chromite and deep liquation of sulfide

Table 2 PGE parameters of deposits related to mafic–ultramafic complex from North Xinjiang and Jinchuan.

Ore district		∑PGE (ppb)	Pd/Ir	(Pd + Pt)/(Os + Ir + Ru)	Ni/Cu	Ni/Pd	Reference
Huangshan East	Rock	1.02–60.27	0.62–2.88	0.38–33.98	1.09–8.03	55–1789	Chai (2006);
	Ore	74.31–178.82	5.76–14.47	0.12–0.81	6.99–39.54	4112–8296	Meng (2008)
Huangshan	Rock	1.20–2.01	12.20–29.50	1.73–3.00	1.28–28.63	2440–5211	Fu et al. (2009)
	Ore	4.36–22.05	5.91–24.21	3.00–11.13	1.18–25.76	1745–7947	
Xiangshan	Rock	6.93–26.79	5.76–14.47	31.38–131.35			Sun et al. (2008)
	Ore	115.22–120.98	24.95–98.25	104.4–115.8			
Tulaergen	Rock	7.37–24.58	6.47–51.75	33.38–127.87			Sun et al. (2008)
	Ore	47.9–486.5			0.09–20.74	14.94–804.6	
Hulu	Ore	40–128	30–50	11.67–35	1.32–2.55	93–233	Li et al. (1991)
Baishiquan	Rock	2.30–19.36	1.36–81.54	0.57–13.91	0.03–1.09	5.61–1871	Chai et al. (2006)
	Ore	78.34	15.19	7.06	0.81	97.71	
Kelatongke	Rock	0.23–43.64	2.55–285.75	0.83–115.44	0–1.73	0.74–263.29	Li (2008);
	Diss. ore	2.72–743.0	6.39–424.53	1.82–303.27	0.28–4.56	54.02–848.5	Qian et al. (2009)
	Injected ore	93.47–1123.02	1.96–549.35	2.96–183.25	0.04–12.08	94.47–1106	
Jinchuan	Rock	9.30–35.60	2.60–15	1.67–10			Wang (2002)
	Diss. ore	98–7159	0.5–6.92	0.6–48.65	(1.85)	(203333)	
	Injected ore	267–850	3.22–14.17	1.87–8.23	(1.56)	(84444)	

may have led to PGE depletion (Wang, 2002). Chai et al. (2006) came to a similar conclusion when studying magma at Baishiquan. However, Sun et al. (2008) arrived at the opposite conclusion at Tulaergen via simulation calculation — namely that there were low PGE contents in the original magma. If one depends on the PGE concentration of original magma for calculations, then it seems that Baishiquan deposit should have a relatively higher PGE mineralization similar to Kelatongke, wheras Tulaergen should be relatively lower. However, Table 2 reflects that such is not the case. All three deposits occur in the post-collision extensional stage of North Xinjiang tectonic evolution (Wang J.B. et al., 2006a) with similar metallogenic settings, and all might be expected to share similar original magma and magma evolution processes according to the above cited $Mg^{\#}$ values of their magmas.

The content of PGE in mafic–ultramafic rocks of North Xinjiang is in the range of 0.2–60 ppb (Table 2), which is one to two orders of magnitude lower than that in layered intrusions such as Bushveld (198–1307 ppb; Gao et al., 2009) and Xinjie in Sichuan, China (159–411 ppb; Liu et al., 2008), and also lower than that in intrusive rocks such as troctolite (400–840 ppb) and olivine gabbro-diabase (10–410 ppb) from the Noril'sk-Talnakh area in Russia (Czamanske et al., 1995). However, the PGE content in the mafic–ultramafic rocks of North Xinjiang is equivalent to that in the Jinchuan deposits, and also to the PGE contents (16.2 ppb and 23.7 ppb) in the upper mantle reported by Brugmann et al. (1990) and Ringwood (1991). Thus indicates that the North Xinjiang PGE contents are not deficient compared to China's largest PGE deposit and the upper mantle.

The injection-type orebody of Kelatongke, which we consider as a product of deep liquation, has PGE contents consistent with densely disseminated ore formed by autochthonous differentiation, but with Pd/Ir ratios similar to or even higher than densely disseminated ore and so similar in Cu/Pd and Ni/Pd ratios that the liquation of deep magma may not cause an obvious separation and/or redistribution of PGE. Conversely, the case of the Jinchuan Cu-Ni deposit is dissimilar to that of Kelatongke as follows: there are obviously different Pd/Ir and Ni/Pd ratios (Table 2) in injection-type ore and disseminated-type ore, with distinctive enrichment of PPGE, but not of IPGE in sulfide minerals (Yang et al., 1997; Wang R.T. et al., 2004b). The PGE content in the Jinchuan and North Xinjiang rocks are very similar, so obviously the parental magmas at Jinchuan were much more voluminous than in North Xiajiang.

It is here considered that the low content of PEG in original magma may result from a low-degree of mantle partial melting (Sun et al., 2008). The differentiated magma is relatively PGE-poor under the low-degree of partial melting because there is no sulfide melting (Lorand et al., 1993); only when the melting degree reaches 23 percent can the sulfide be completely melting and enter the melt (Wendlant, 1982).

4.2. Nd isotopic characteristics of host mafic–ultramafic rocks in North Xinjiang

The Sr and Nd isotopic geochemistry of post-collisional ore-bearing mafic–ultramafic rocks from North Xinjiang (Fig. 4) is quite different from that of other PGE-bearing complexes in China and the world at large in the following ways: Cu-Ni sulfide deposits (North Xingjiang) have $\varepsilon_{Nd}(t)$ values ranging from +1.67 to +11.70. and the $(^{87}Sr/^{86}Sr)_i$ values ranging from 0.7016 to

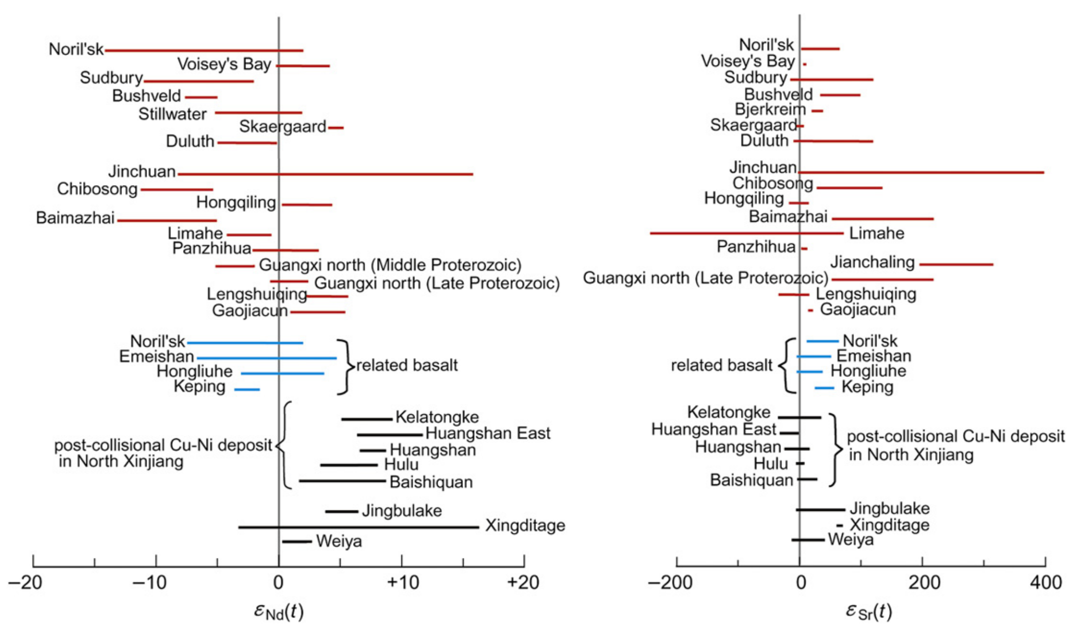

Figure 4 ε_{Nd} and ε_{Sr} value of Cu-Ni(-PGE) deposit from North Xinjiang and other areas. **Data source from**: Noril'sk -Czamanske et al. (2000) and Hawkesworth et al. (1995); Viosey's Bay - Amelin et al. (2000); Sudbury -Faggert et al. (1985) and Naldrett et al. (1986); Bushveld -Carr et al. (1999) and Maier et al. (2000); Stillwater -Lambert et al. (1994); Skaergaard -McBirney and Creaser (2003); Duluth -Lightfoot and Naldrett (1984); Jinchuan -Xie et al. (1998) and Zhang et al. (2004); Chibaishong -Zhao (2006); Hongqiling -Wu et al. (2004) and Yang et al. (2005); Baimazai -Guan et al. (2006) and Wang (2008); Limahe -Zhang et al. (2007); Panzhihua -Zhang et al. (2007); Guibei -Zhou et al. (2003); Jianchaling -Chen and Pang (1994); Lengshuijing -Shen et al. (2003) and Zhu (2004); Gaojiacun -Zhu (2004); Noril'sk basalt -Hawkesworth et al. (1995); Emeishan basalt -Zheng (2006); Hongliuhei basalt -Pan et al. (2008); Keping basalt -Jiang et al. (2004); Kelatongke -Chai (2006), Jiang et al. (2009), Li et al. (1998), and Wang and Zhao (1991); Huangshan East -Chai (2006); Huangshan -Li et al. (1998); Hulu -Xia et al. (2008); Baishiquan -Chai (2006); Jingbulake -Chen et al. (1995); Xingditage -Li et al. (1998); Weiya -Wang et al. (2008).

Table 3 PGE abundance in different rocks or layers of the earth (ppb).

Rock/Layer	Oceanic crust	Continental crust	Original mantle	MORB	Continental komatiite
Pd	<0.2	1.0	3.9	0.06–0.113	5–15
Pt	2.3		8.7	0.07–0.142	6–22
Rh	0.2		1.7	0.01–0.012	0.5–1.4
Ir	0.02	0.1	3.2	0.028–0.04	0.26–1.50
Data source	Taylor and Mclenman (1985)			Hartmann (1996)	Brugmann et al. (1987)

0.7067 with $\varepsilon_{Sr}(t)$ values of −36.3 to +36.5; V–Ti magnetite deposits (e.g. Weiya) have ε_{Nd} (t) value of +0.22 to +2.61, $(^{87}Sr/^{86}Sr)_i$ values ranging from 0.7033 to 0.7071 and $\varepsilon_{Sr}(t)$ values of −13.3 to +41.1. The distinctively positive $\varepsilon_{Nd}(t)$ values and low initial ratios of Sr display characteristics of a depleted mantle source that possibly assimilated continental crust. The narrow range of $^{206}Pb/^{204}Pb$ ratios, 17.67–18.38, in three Cu-Ni sulfide deposits in North Xingjiang (Chai, 2006), may indicate that all were derived from similar parental magma sources. It is worth noticing that some non-PGE mineralized Cu-Ni deposits such as Hongqiling of Jilin, as well as Lengshuiqing and Gaojiacun of Sichuan, also have Sr and Nd isotopic characteristics similar to those found in North Xinjiang.

There are two explanations for the generation of depleted mantle sources. One is that they are products of partial melting of the depleted mantle (Han et al., 1999), whereas the other may be that the normal mantle assimilates a "depleted" crust. North Xinjiang, and in particular the areas surrounding the Junggar Basin, are not underlain by Precambrian continental basement, but have what most researchers consider to be "oceanic crust basement" or "immature continental crust" (Coleman, 1989; Xiao et al., 1990; Wang J.B. et al., 2004a). It is characterized by well-developed ophiolites, low-grade metamorphism, and a wide-distribution of granitic plutons with positive $\varepsilon_{Nd}(t)$ values. The parental magma of the mantle-derived deposits in North Xinjiang may assimilate this type of "depleted" oceanic crust characterized by a number of distinctive features, listed as follows: first, the related magma is of a "water-rich" nature because the mafic-ultrafic rocks usually own pegmatite and miarolitic textures and contain plentiful original hydroxy minerals such as biotite and hornblende (Tu, 1993; Wang Y.W. et al., 2004c, d); second, incompatible elements like LILE and LREE are enrichment in the rocks (Wang et al., 1987; Pan et al., 1994; Ran and Xiao, 1994; Chai, 2006; Wang Y.W. et al., 2006b; Zhang Z.C. et al., 2006a; Sun et al., 2007); third, the deposits usually have a spatial relationship to basement ophiolites and have ε_{Nd} values similar to them (ε_{Nd} values of the five ophiolite sets of North Xinjiang are +2.8 to +11.71; Zhang and Huang, 1992; Ma, 2007; Lei et al., 2008). The post-collisional mantle-derived magma related to Cu-Ni mineralization cannot have a source be independent of this basement. This explains why North Xinjiang mafic ore-related magmas should be poor in PGE, because oceanic crust, i.e. ocean ridge basalt (MORB), represents the lowest degree of partial asthenospheric melting, and its PGE abundance is the lowest in major layers of the earth (Table 3).

From the above analysis, the post-collisional, mainly Permian, Cu-Ni sulfide deposits of North Xinjiang indicate factors favorable to sulfide liquation in ore-forming mechanisms because of the assimilation of continental crust. However, although the distinctive oceanic basement of this area drives Cu and Ni values higher, it is the low PGE background of the magma source that makes this environment unfavorable for the enrichment of PGE mineralization.

In terms of the tectonic settings of most word-class PGE deposits around the globe, all major PGE-bearing complexes occur in stable land masses with paleo-continental crust basements, as can be seen in the Bushveld complex in the African shield; in the Noril'sk-Talnakh ore field on the Siberian platform; in Duluth, Sudbury, Thompson, Stillwater, Muskox, Lac Des Iles, and Coldwell on the North American platform; in Pechengga and Portimo in the Baltic shield; in Kambalda on the Western Australia shield; and in China's Jinchuan on the North China platform (Tang et al., 2007), and Jinbaoshan and Yangliuping on the Yangtze landmass (West margin) (Tang et al., 2007). Paleo-continental crust basement has a high degree of maturity and contains higher PGE than that of oceanic crust (as seen in Table 3), so that the original magma source (usually with negative ε_{Nd} value) produced by mixing with mantle magma is accordingly PGE-rich, making it that much easier for PGE to concentrate and mineralize during the late stage of magmatic evolution and during the process of sulfide liquation.

Additionally, the formation of PGE deposits requires the complex coupling of multiple factors, but the metallogenic conditions in North Xinjiang discussed in this article depend simply on two factors, the magma source and the liquation mechanism. Another important mechanism for PGE mineralization, the ore-forming fluid, will be addressed in further studies.

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